Threat of drones and UAVs and UACVs[1]

In the latest two decades emerged and became (quite) widely used UAVs from the smallest quadcopters up to the largest such as Global Hawk.

Thanks to the more and more advanced digital electronics it became possible to design such flying vehicles which can carry lightweight digital camera systems. The drones nowadays can fly without direct human control using only inertial navigation system (INS) + satellite (GPS or similar) navigation without receiving regular input via radio. Comparing to direct radio controlled (RC) vehicles this makes a lot more easier to use them well and safely. Not only small helicopters and quadcopters but conventional flying airplane like drones can be used by operators without special piloting skills and many times requires radio control input from the operator.

The main problem of the UAVs size and engine which makes in many cases hard their detection and destruction. Even just detecting these lightweight and very small flying objects is a not an easy task. Because of their small size – some of them have less them 0.5-1 meter main dimension (R <0.25-0.5 m) – and quite silent electric motors is very hard to detect them. Even if it uses small piston engine the emitted noise is nowhere close to conventional airplanes of helicopters. From few hundred meters they are undetectable by noise with human hearing.

Also, thanks to their composite structural material with very few metal components their radar cross section is small and it is especially small of the RCS of small quadcopters.

Because of the electric or small power combustion engine even with IR cameras is hard to spot them. Comparing to jets or turbo-propelled driven aircraft which produce lots of hot flue the electric driven UAVs with 1-10 kW engines literally does not produce waste heat. The surface of an electric motor can be hot for human touch but even 50-100C surface temperature is nowhere close to 500-1000 C gas temperature (plume) of jet or turboprop engines. The 10-100 kW combustion engine driven aircraft are also harder to spot because the IR signature is smaller to human piloted aircraft.

Above left is a very small quadcopter above right is the MQ-9 Reaper UACV. The drones in size similar to MQ-9 are not an issue for army air defense they are enough big for radars and engine produces enough exhaust gas to be downed by IR guided missiles. IR SHORAD has engagement range up to 3-4 km altitude and 4-6 km range while the radar SHORAD can have 6-10 km maximal engagement altitude with 10-20 km engagement range. The latter SAMs can act as area denial against MQ-9 category drones. Such kind of target are enough large for proximity fuse of the missiles.

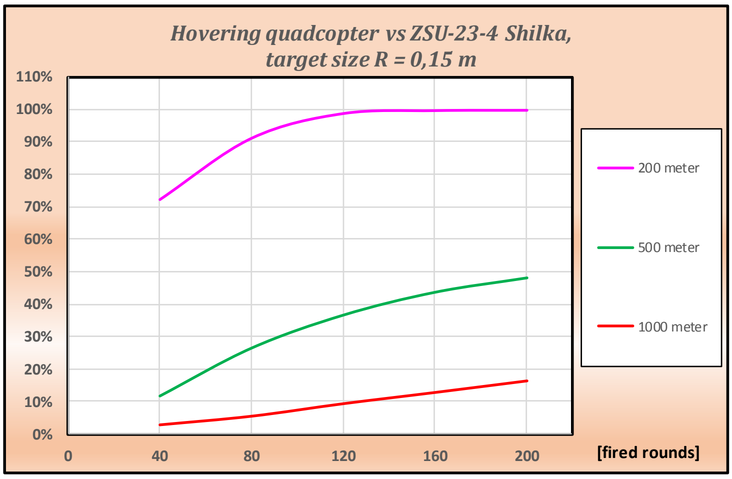
[1] *Unmanned Aerial Vehicle, Unmanned Aerial Combat Vehicle*

The more and more serious issue are such small drones similar what we can see above left. They are way too small for any conventional air to air missiles and even for MANPADs.

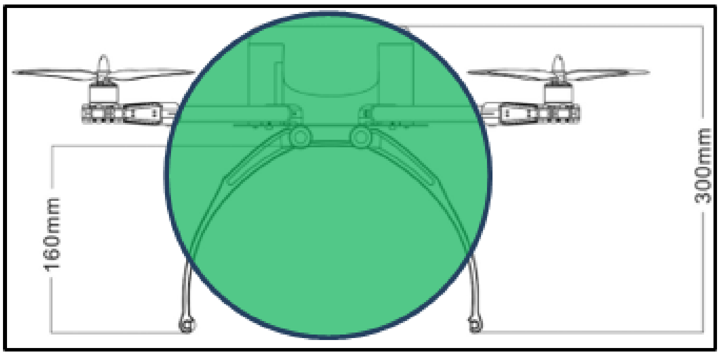
The size and physical properties of very small UAV currently strongly limit of the available defensive options with currently available equipment. A conventional anti-aircraft guns are designed against helicopters and airplanes which are mostly one or even two scale larger targets comparing to drones or very small quadcopters.

Even against human piloted fast flying airplanes hundreds of ammunition is needed for high kill probability at long range. Using the 2K22 Tunguska, Flakpanzer Gepard and similar AAA equipment is close to zero the chance of hit against very small quadcopter at reasonable distance because of the random dispersion of the guns. For example, the 23 mm gun of the ZSU-23-4 Shilka has the following parameters.

Flight time [s]	Distance [m]	Velocity [m/s]	Dispersion (CEP)[2] [m]
0	0	980	0
0.2	200	860	0.4
0.6	500	700	1.2
1.4	1000	520	2.8
2.5	1500	400	5
4.17	2100	310	8
5.5	2500	280	11



If we assume a target of a small quadcopter with D = 0,3 meter size (see of the right) only at 500 meter target distance the probability of a single hit is only about 50% target with a 200 rounds (this means about 4 second long) burst.



At 1000 m the calculated chance to hit is less than 10%. Even for this low success rate engagement we have to assume that a Shilka or similar AAA system is able to track continuously very small targets, there is no aiming error, target does not move and reacts on the air defense fire, etc...[3]

On a video[4] we can see even at 100 meters distance on a short burst the dispersion of high rate of fire 2K22 Tunguska system. A very small drone with R = 0,15 m main dimension would survive the short burst (with about 40 rounds). The Cold War and legacy AAA systems were designed against airplanes and helicopters not very small drones. These kinds of targets are enough large to make sufficient the guns with high rate of fire considering their dispersion while they use cheap rounds with impact fuse.

2 *https://en.wikipedia.org/wiki/Circular_error_probable*

3 *In Hungarian was made a very long article by me about modeling of AAA systems against different kind of targets with statistical mathematical model based on known parameters of same AAA systems. The source if the diagram and the values is that document. Maybe one day it will be translated into English.*

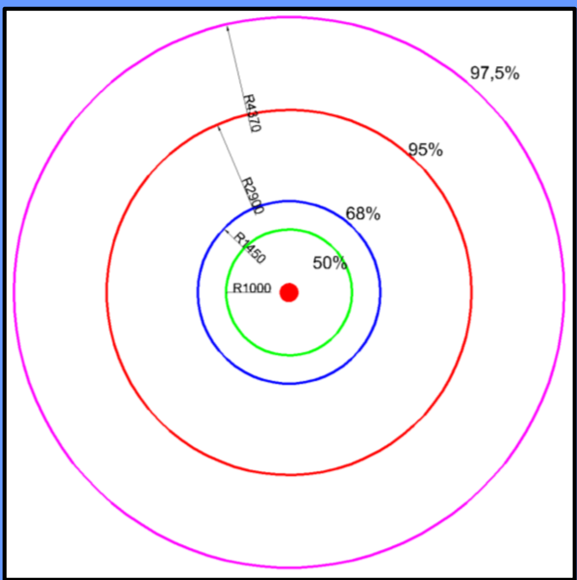
4 *https://www.youtube.com/watch?v=ruC4IhTxLgs&feature=youtu.be&t=369*

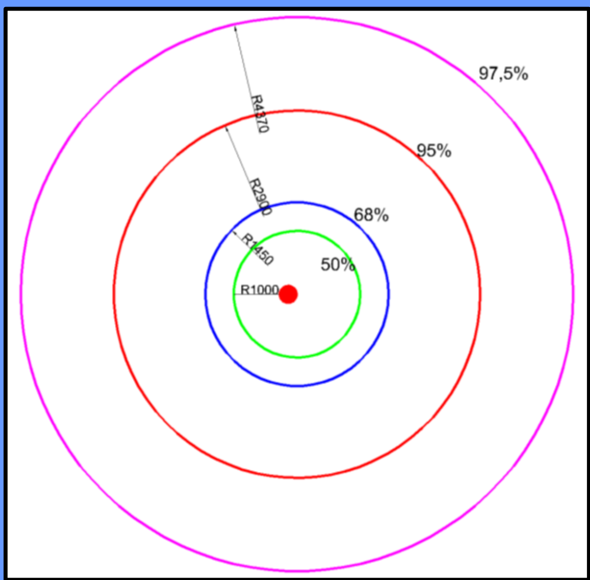
The Cold War legacy AAA systems have problems even tracking small targets with radar on a demonstration video Pantsir tracked optically the target not with radar.[5]

The effect of the dispersion comparing to aiming point, the center of the wooden plate. Is not a single hit closer than 15-20 cm from the center regardless the distance was only 100 meter. This dispersion is acceptable for shooting down airplanes but against very small drones is simply makes ineffective the air defense gun.

The demonstration of the Pantsir was very funny from the POV who understand what exactly happened. The cause of being funny was the off aiming at the beginning of the video because in reality it did not have any effect on chance to hit. Target distance was about 400 meters.

The dispersion of the gun is so large at 400 meters the very minor off aiming does not have any effect of chance to hit. The dispersion (CEP = circular error of probability, it is the radius where 50% of shot are) of the Pantsir is similar to ZSU-23-4 Shilka which is about 0,5 meters at 400 meters of distance. This means about 50% of rounds will hit within this radius bit **it also means the total dispersion radius is about 4 (!) times larger considering characteristics of the bullet distribution**.





Moving off a bit the aiming point because of the large dispersion radius was meaningless as we can see in the drawings above. The percentage values show the confidence level at certain radius from the center of dispersion. On the drawing above right the small quadcopter size "target" is moved off from a center a little bit. This what happened in the video. The target remained still almost the center of the dispersion **which means the chance for the hit is virtually remained the same regardless of the off aiming**.

5 https://youtu.be/pdmBBaTQ6q0?t=1351

Even for first attempt with a 40 round salvo was achieved a hit on the leg of the drone what could survive. The first hit on the leg was **a very, very lucky and unexpected** event but and after shooting about 160 more rounds happened which was not so unlikely anymore especially against a stationary target.

Therefore, the drone later was not downed after "the first volley of 40 rounds" as the reporter said because many times were fired a 40 rounds long burst before the quadcopter was destroyed. In fact, the model which I used predicts that chance to hit from about 200 shot at 400 meters is about 65%.

The case is similar to playing heads or tail game. Sooner or later will be balance between the two outcomes. In the case of this demonstration it could be predicted after how many shots is required for a certain confidence level of destroying the target. The video simply used that. Fired with off aiming and happened a very "unlucky" hit from the point of view of the demonstration. When finally reached the quantity of rounds when the fatal hit could be expected it could say they did it with "first attempt" the target. While in reality the drone was destroyed but not because of the "correction" of the off aiming. The video just proved two things:

1. Statistics is not an easy field of math without understanding the effect of dispersion and probabilities.
2. Shooting down a small drone with acceptable effectiveness with conventional AAA systems is simply not possible.

400 meters distance with current recon capabilities of drones is simply means way under estimated target distance. Drones can provide good quality image from much larger distance which means even more longer engagement time and ammo is required for destroying a single hovering quadcopter.

Shooting down UAVs and small quadcopters at acceptable distance is also not possible also with small arms, rifles and machine guns. On a video[6] we can see how likely is the hit and kill on a drone which flew minutes ahead of many, many gunners.

The conclusion is different kind of equipment are required against the threat of recon of suicidal drones/loitering munitions.

Regardless very small drones can stay airborne for a short time with limited operational range (30-60 min, 0.5-5 km with Wi-Fi 2.4 GHz remote control but they can fly 30-50 km in autonomously) they can provide essential intelligence data in real time. Some drones is able to operate even at night with infra-red cameras. These drones are very helpful to create a good situational awareness on the battlefield.

Even just because of the recon capability it makes desirable to destroy the drones instead just jam or disable them with electronic jamming. Sooner or later suicidal drone swarms can be the threat[7] which can perform coordinated strike against unarmored or lightly armored vehicle. In case drones will become even more cheaper and intelligent every single soldier can be hunted by small drones. This is not a joyful vision of the future...

6 https://www.youtube.com/watch?v=rGLxKXtkHpY

7 https://www.youtube.com/watch?v=DjUdVxJH6yI
https://youtu.be/-HZHRTEYTVg
https://youtu.be/8FukTsKmXOo

Considering what we can see on the drone swarm video it seems feasible to create such an aircraft carried pod or cruise missile which can carry lots of small drones. A fighter aircraft of a cruise missile such as the Taurus KEPD 350 under the radar horizon could carry the drones enough close to target. The target for example can be an S-300/400 battery. From 30-40 km the target the drones can be released depending from the terrain

The currently used air defense systems are not capable to destroy such high quantity of very small targets. Even if they could it is not economically viable. Only about 2-4 fighter or half a dozen cruise missile could release 50-100 small drones.

These small drones would not be able to carry more than 1 kg warhead but this is more than enough to damage or even destroy the fire control radar and other crucial system elements in the battery. Without the fire control radar the combat potential of and S-300/400 battery (or similar Patriot) is zero. If the fire control radar has been disabled the battery could be destroyed with conventional weapons if is protected by Pantsir, Tor-M1 or other similar system. In case the SAM battery has these short range SAMs for protection at least much less firepower is enough to penetrate the remaining element of the IADS but the area denial capability by the S-300/400 is disable for a while...

Of course, such drones require some kind of EO/camera to find their targets and some kind of “AI” for target recognition but on current technology level this is not sci-fi anymore.

The imagined scenario above is nice but if the S-400 SAM had over the horizon capability it would (partially) eliminates the concept. In case the terrain makes possible for the long range target acquisition radar the early detection or AWACS is available with data link the “mothership” fighters and cruise missiles can be attacked and downed even before they reach the 30-40 km, the range limit of ordnance release location. (S-400 + A-50U/A-100 will be able to launch under the horizon as well as S-350 Vityaz. This is not unique Patriots with AR guidance also will be able to do this.) This means much gong range drones would be needed. But cheap drones for swarms are on the opposite side of the scale where larger drones are sat. Both cannot be done in the same airframe...

So, in the near future it may be possible dealing some “soft” target with swarm of small drones to prepare the battlefield for conventional weapon systems but using as a general strike weapon is another thing. They are too small and have too small range against many targets. Many types of targets are to armored or is too fast (helicopters and airplanes) to be able to intercept them. Regardless they may not able to destroy a tank or infantry fighter vehicle they are able to downgrade their combat potential by destroying their sensors. This means even a less advanced tank can deal with more advanced what lost its full potential the drones can change the balance between the fighting sides.

The task is given. The currently used small drones and quadcopters and within the foreseeable future smaller drone swarms have to be dealt by air defense. The drones likely will challenge the capabilities of air defense. It is not feasible to counter or destroy every small drones with MANPADS with 50-100k USD cost or even more expensive missiles. Comparing to these most of civilian small drones are far more cheaper. Of course most of civilian does do not have jam resistant communication.

The loiter capacity ammunitions (LAMs)[8] are in the minds of designers since the early '90s. They were part in the Future Combat Soldier program as NLOS-LS (Non-Line of Sight Launch System).[9] The whole FCS was cancelled including the special munition because of its high cost at that time. The demand for such drone is dated back decades but nowadays it seems to possible to design such system with an acceptable price tag.

The civilian drones can be used as an alternative regardless they not met with the specification of the NLOS-LS LAM (72 km range and 30 minutes loiter time) but with 20-30 minutes max. flight time they are better than nothing. The weakest point of LAM drone swarm is the in between communication of the drones. In case the connection is broken or jammed the drones may can fly and find their targets only autonomously based on last target coordinates and their camera system but this needs a very advanced software.

The civilian drones mean a considerable threat because they are available for a very small price and many armed forces in the word are not (yet) well prepared against them. They are ideal tools for COIN/low intensity conflict environment.

Even professional armed forces many times rely on civilian drones because they are easily accessible and the information and recon data what they can provide in many cases is almost identical or identical what military drones provide.

An RQ-11 Raven (on left) is a hand launched drone. It cost was little above 20 000 USD in 2017. The Raven before 2015 had only forward looking camera and because of its airplane like drone it has much restricted racon capability comparing to quadcopters or octocopters with rotatable cameras. Since 2015 RQ-11 can be equipped with a better camera system but it made even more expensive the drone. Similar civilian drones or small quadcopter in some cases cost only a fraction of the RQ-11.

Against drones mostly electronic jamming are used especially against civilian ones which are not protected. The problem as the drones become more advanced as less will be useable the jamming if drones will be able to navigate using inertial navigation (current gyroscopes even is smartphones are enough good for short time) combining with terrain/shape recognition. Of course, GPS or any satellite navigation system can be jammed. But in this this kind of navigational aid for the jammer also may be unavailable for the jamming side either.

For jamming the drones relatively large and heavy equipment is needed. The handheld jammers has only some dozens of meter range. Another issue is the frequency. Currently drones uses the 2.4 GHz frequency range. The armed forces can be equipped with the necessary jammers... then maybe somebody start to build drones which uses different band range. Even every kind of jammers are supplied the friendly forces it can jam the short-range communication devices and well as civilian cell phone communications which is unacceptable in some situations.

8 *https://youtu.be/1tZB44fL5tw* , *https://youtu.be/qIYZiTqenJs*
https://dronecenter.bard.edu/files/2017/02/CSD-Loitering-Munitions.pdf

9 *https://en.wikipedia.org/wiki/XM501_Non-Line-of-Sight_Launch_System*

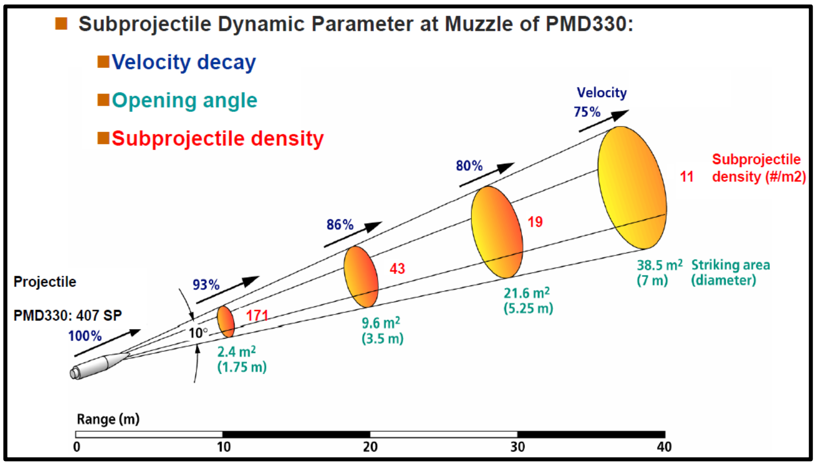
Because of the side effects and only preventive mode of the jamming it would be better do destroy the drones. This could be done with smaller or cheaper missiles, guns with special munitions (AHEAD[10] or airburst) or maybe with energy (laser) weapons and the last option is using the hunter drones.[11]

Luftvärnskanonvagn (lvkv) 9040, special variant of the CV90 IFV with anti-drone equipment.

Let's start with the guns. In the near future automatic or remote controlled gun turrets/stations can help the anti-drone warfare. Turrets with sensor also can be applied on infantry fighting vehicles, a self-contained system which consist 360 degree coverage optical and/or IR/EO seeker. The problem such kind of system cost hundreds of thousand USD without the gun and the vehicle itself.

Such weapon system is the special variant of the Sweden IFV CV90. For more than 10+ year Sweden developed the 40 mm Bofors gun with 3P programmable ammo but so far nobody has been ordered.[12]

Even more specialized and dedicated AAA system is the Skyranger (on the left) system with AHEAD ammunition which is the mobile version of the Skyshield system.[13] As on videos have been demonstrated it is able to track and destroy very small quadcopters from at least about 500 meters only with some rounds as well as larger airplane like UAVs either above 1 km (target was an MTX type drone).[14] Because of the technical requirement of the AHEAD technology so far has not been developed AHEAD type munition smaller than 30 mm caliber. Against such small target as quadcopter to achieve high probability of kill with short burst at least 30 mm but rather 35 mm size ammo is needed. Against larger target heavier submunitions also demand the 35 mm caliber.



The subprojectile density in case of different burst distances with 35 mm PMD 330 ammo.

10 https://youtu.be/d0oHvqIUEmY

11 https://www.youtube.com/watch?v=PpqFNSpANFM
https://player.vimeo.com/video/364333850, https://bit.ly/379OlGC , https://youtu.be/QwDykpIQkfc

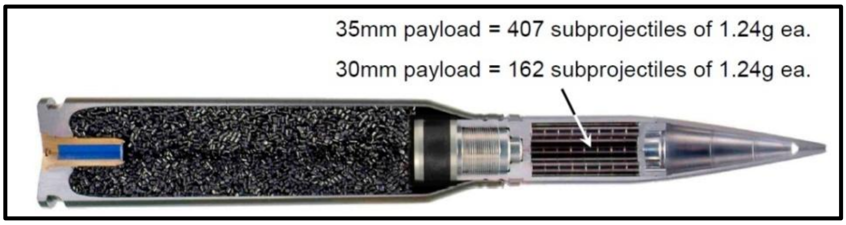
12 https://www.youtube.com/watch?v=Nj0q-sxKrvq

13 https://youtu.be/h3zhkpVsn28
https://planesandstuff.files.wordpress.com/2014/05/janes-system-upgrades.pdf

14 https://www.youtube.com/watch?v=h3zhkpVsn28&feature=youtu.be&t=117
https://www.mtx.pmrobotics.ch/

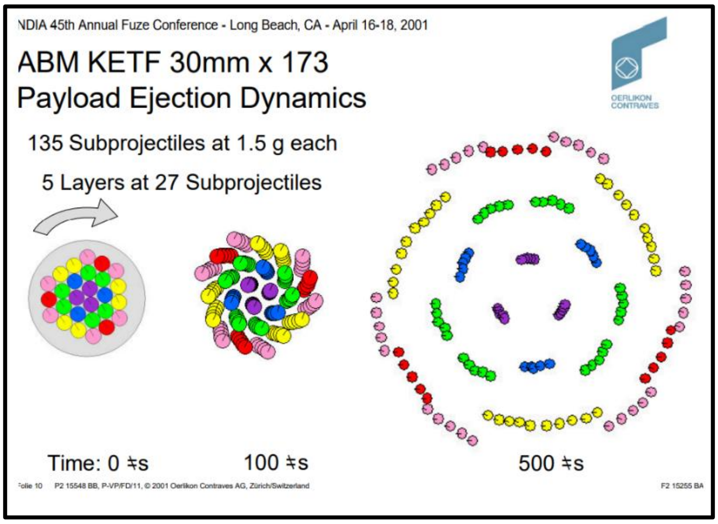
Designation	Payload	Weight of sub-projectiles
PMD062	152	3.3 g
PMD330	407	1.25 g
PMD375	860	0.64 g

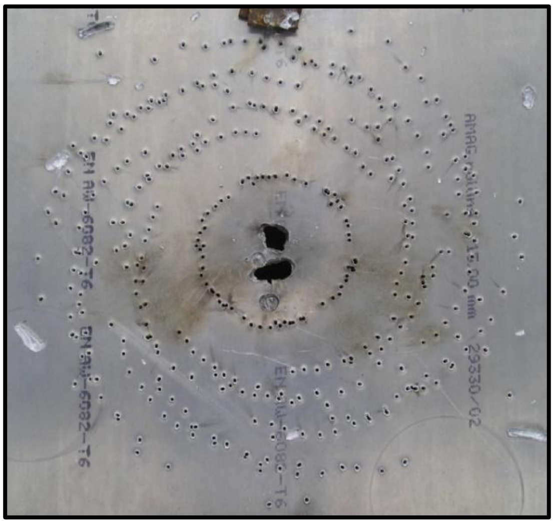
AHEAD ammo types in 35 mm caliber.[15]



Difference between 30 mm and 35 mm in subprojectile quantity which has strong impact on projectile density.

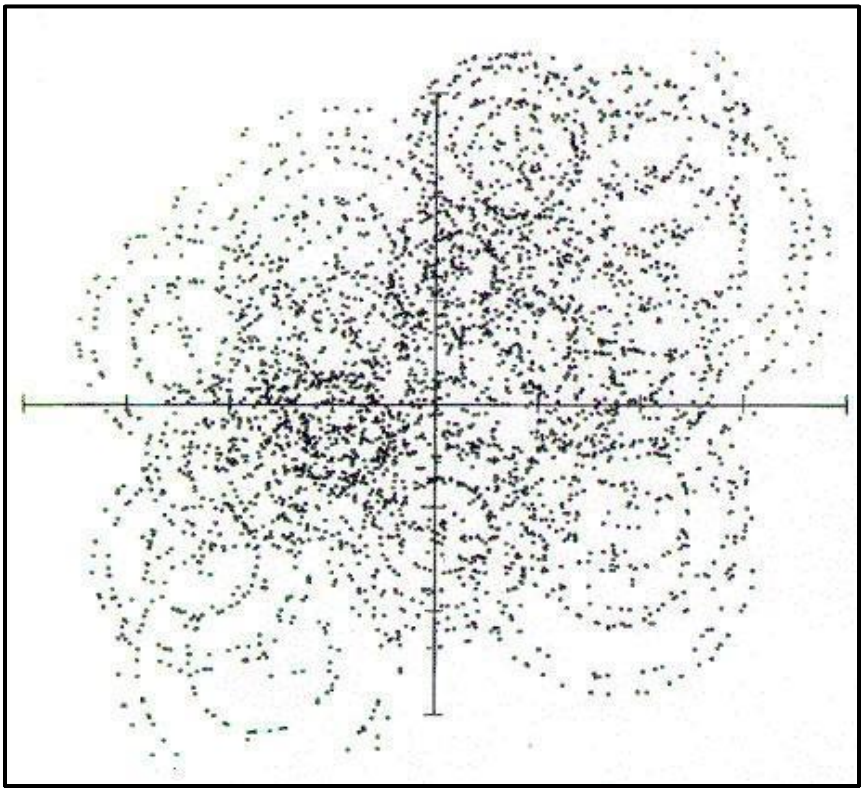
The diameter of the AGM-65 Maverick missile is only 0,3 m. Even at about 2 km distance some rounds can cause such extensive damage on the missile. Similar system to Skyranger installed on ships as CIWS would outclass any older conventional high rate of fire system such as Phalanx CIWS or any similar.





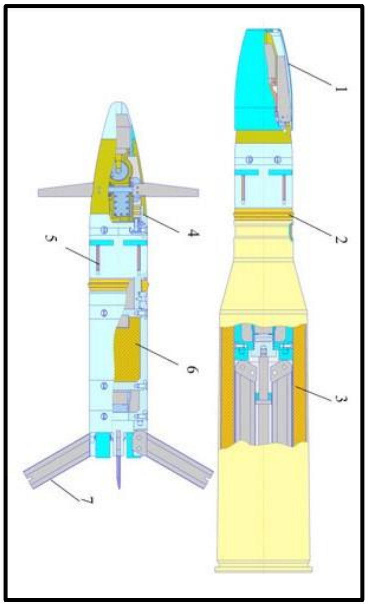
The dispersion characteristics of the 30 mm-es KETF ammo (above left) and the 35 mm (above right).

15 https://apps.dtic.mil/dtic/tr/fulltext/u2/a393758.pdf
https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2011/gunmissile/Tuesday11786_Bradick.pdf
https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2009/gunmissile/7923paulissen.pdf



The covered area with the Skyguard/Skyshield system with 25 round salvo (about 1,5 sec long) using 35 mm ammo.[16] Is simply no way to survive such subprojectile density. The scale of the drawing are meters, the crosshair covers 4x3 meter. Regardless of the dispersion of the gun at longer range the subprojectile density is enough big to destroy anything only with about 1-2 dozen rounds comparing to conventional AAA system which cannot achieve a even a single hit on target even with hundreds of rounds.

There are also other concept against drone with multi-purpose capability. Based on BMP-3 infantry fighting vehicle (IFV)[17] with a 57 mm gun and radio fuse laser beam riding ammo was developed the 2S38 Derivatsiya ZAK-57.



2S38 Derivatsiya, new turret & gun with the necessary electro-optical equipment and the intelligent ammunition.

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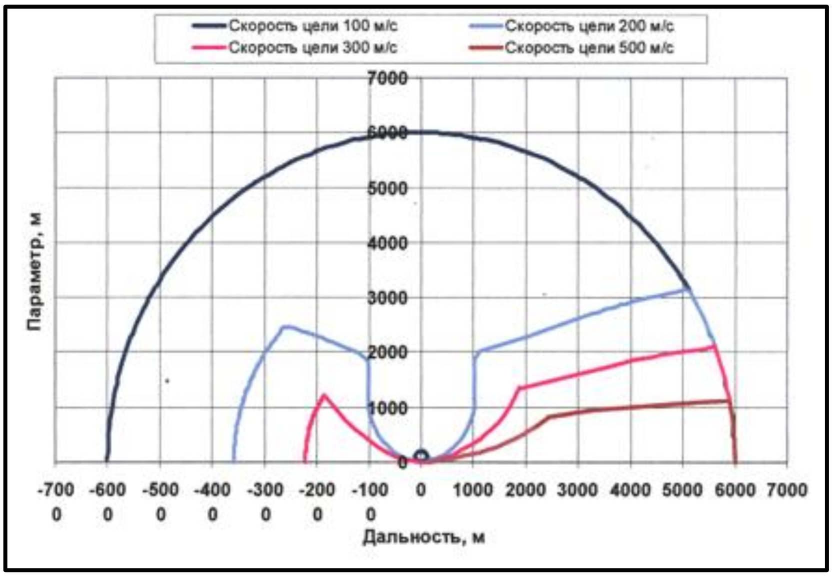
16 http://www.repulestudomany.hu/kulonszamok/2007_cikkek/nagy_norbert.pdf
https://bit.ly/2Wxan3L

17 https://goo.gl/H8QhAQ, http://www.military-today.com/artillery/2s38_derivaciya_pvo.htm



The engagement zone of the 2S38 Derivatsiya, system.

The conception of the 2S38 makes possible using a single unit against drones, helicopters and even against other IFVs. The latest and most advanced IFVs are quite well protected against 25-30 mm automatic guns (except close range engagements) therefore the new long range and guided munition can provide range and accuracy advantage comparing to IFVs equipped with conventional 25-30 mm autocannons.

Another benefit of the 57 mm caliber for the ammo not only being "intelligent" but with such size is possible to cause such damage which exceeds smaller gun calibers. Because the ammo is guided it has pinpoint accuracy up to max. engagement range comparing to conventional guns which has (natural) dispersion. The dispersion (CEP value) of conventional 25-30 mm autocannon at 1000 m is about 0,5-1 miliradian (mil). This means APC/IFV size targets rarely can be hit above 3 km distance even about firing two dozen of rounds. The armor penetration capability of the 25-30 mm rounds is low comparing to frontal armor of IFVs.

As we can see on the engagement diagram above with zero offset distance at low level in theory even airplanes can be engaged up to 300 m/s (M0,9) speed up to 2-3 km altitude and 6 km distance which is close to engagement zone of the older MANPADs. Against helicopters (up to 100m/s) the 2S38 has very similar only a slightly smaller engagement range than 2K22M Tunguska which means it has almost the same area denial capability. Against low quantity drones the 2S38 Derivatsiya seems a suitable solution especially it is a multipurpose vehicle. The intelligent 57 mm round does not have to produce a direct hit because it can have airburst warhead either while it retains the pinpoint accuracy.

There is a strong trust and hope in energy weapons. Solid state lasers can be used in good conditions at least against small drones today.[18] In military exercise and demonstrations some lasers have been proven[19] but they have not been deployed on battlefield in real conflicts. Currently is about 20-30 kW lasers are available where the cooling and portability is solved but even such low power lasers (comparing to need for other targets) are very expensive. Another problem their performance is limited by the weather.

18 https://www.raytheon.com/news/feature/laser_dune_buggy.html
The vehicle does not have an armored operator compartment which makes undesirable in a combat environment but at least is light and any helicopter of transport aircraft can carry. https://youtu.be/IiEXkqIbKsY

19 https://bit.ly/3397C7M

On smaller scale handheld equipment is also available such as the Pike[20] system. The Pike missile is launched from a handheld grenade launcher. The missile is laser guided the illuminator is attached on the launcher. The missile is semi-active laser guided the target has to be illuminated continuously which requires certain manual skills from the operator to keep the laser beam on the target during the whole engagement.

The weight of the missile is 0.77 kg (without the launcher tube), warhead weight is only 0.27 kg, length of the missile is 43 cm (16.8 in) According to manufacturer its rage is 2 km but it is hard to imagine than any operator can aim and hold on moving targets the laser for longer time. The missile kinematic range likely far outranges the limitation of the aiming.

The Pike missile and one possible launch mode with a handheld grenade launcher.

Currently it has not seen on vehicle mounted version of the Pike but in theory it would be a usable solution installing a complete automatized system on tanks or IFV. At first step it would solve the issue if target tracking with laser. The carrying capacity of these vehicles are sufficient for installing small turret which can be equipped with the necessary EO/IR sensors and some (about 6-12) missiles on each turret. These extra sensors are required besides the base sensors of the combat vehicles to ensure the automatic search and track capability while the vehicles still retain of its original combat potential. It is possible that an existing system has to be sacrificed in exchange this anti-drone system (for ex. remote controlled machine gun) but in case 1-2 modified tank or IFV can ensure the protection of a company size unit (about 10 tanks or IFV) this tradeoff seems acceptable.

Summarizing all the mentioned issues and solutions above:

- The civilian and small military drones are means larger and larger threats especially the upcoming drone swarms and suicide killer drones.
- So far universal hard kill protection against drones are not available currently mostly electronic jamming is used (soft kill).
- The currently developed systems try to deal with threat the following ways:
    1. Intelligent munitions, rapid fire combining with AHEAD or airburst ammo up to 40 mm caliber down to 30 mm.
    2. Intelligent guided munitions.
    3. Energy weapons.
    4. Smaller and cheaper missiles comparing to conventional anti-aircraft missiles because currently available Cold War legacy systems are too expensive for the goal and their capability is limited in many areas.
    5. hunter drones
    6. electronic jamming

[20] https://www.raytheon.com/capabilities/products/pike/